
**FORMATION EVALUATION IN LOW RESISTIVITY LOW CONTRAST
(LRLC) SHALY SAND THIN LAMINATION; FORWARD MODELING AND
INVERSION OPTIMIZATION USING GENETIC ALGORITHM**

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ABSTRACT

Formation evaluation in thin bed lamination is challenging and classic petrophysical workflow would results in underestimation of true hydrocarbon pore thickness and consequently underestimation of hydrocarbon in place in oil and gas fields. Due to deficiency of conventional well logs to detect thin bed shale sand laminations, they appear as non- hydrocarbon bearing low resistivity interval on well logs. True log response cannot be recorded in thin bed shale sand lamination intervals since thickness of these layers is lower than logging tool resolution. Logging tools can only record the average log response of shale and sand together – rather than true response of sand - anywhere the thickness of each lamination falls below vertical resolution of logging tools. Forward modeling and inversion workflow was applied in a thinly laminated shaly sand reservoir to calculate true hydrocarbon pore thickness. The process of forward modeling and inversion was optimized by using Genetic Algorithm approach by developing a computer code. A new workflow for formation evaluation was proposed for formation evaluation in thin bed shale sand laminations and verified successfully. The result was fully integrated and verified with core, well log and production data. True hydrocarbon pore thickness was increased, and new perforation interval was suggested based on the findings.

Keywords: Low Resistivity Low Contrast (LRLC); Formation Evaluation; Shaly Sand Thin Lamination; Forward Modeling and Inversion; Genetic Algorithm

INTRODUCTION

Lack of considerable exploration in conventional reservoirs, exploration and development of Low Resistivity Pay (LRP) reservoirs have been accentuated over last decades. Low resistivity pay intervals are defined as formations which deep resistivity readings is low (same range as shale and water interval) but only hydrocarbon would be produced after production commenced.

Low Resistivity Pay (LRP) formations involves:

- Thin Bed Laminations of Sand and Shale
- High Capillarity Facies as Micrite Porosity
- Fractured Reservoirs
- Presence of Paramagnetic Minerals as Pyrite

On the macroscopic scale (between grain-size and bed-size) there are two main types of deposition that can cause anisotropy: (1) alternating thin sand–shale laminae, and (2) alternating fine and coarse micro layering. Alternating fine and coarse micro layering can cause anisotropy in perfectly clean sands with no shale content. This type of anisotropy is often associated with crossbedding, that is, wind or water-deposited strata arranged at different angles relative to the main bedding plane. In some cases, there may be thin cemented sandstone layers separating cross-beds [1,2]. Alternating facies change from Wackstones to Packstones to Grainstones in carbonates has same effect by making anisotropy which would affect deep resistivity.

An important case of low resistivity pay interval is shaly sand thin bed lamination which will be discussed in this paper. Sand true response cannot be recorded when thickness of sand or shale layer is less than vertical resolution of logs. So thin bed lamination appears as dispersed shaly sand interval on logs. Resistivity log reading would be around shale resistivity range. Therefore, by classic well log interpretation, thin shale sand lamination interval would be interpreted as non- reservoir. Thin lamination thickness is considered to be more than 1 inch (core plug resolution) and less than 2 ft (conventional log resolution).

Assessing original hydrocarbons in-place (OHIP) is corner stone of all reservoir assessments. OHIP at surface conditions can be calculated by volumetric equation:

$$OHIP = A \cdot h \cdot \phi \cdot (1 - S_{wi}) / B \quad (1)$$

$$OHIP = A \cdot HPT / B \quad (2)$$

Where:

OHIP = Original hydrocarbon-in-place [stb]

h = Average thickness of HC-bearing interval [ft]

S_{wi} = Average initial water saturation of HC-bearing interval [frac]

ϕ = Average total porosity of HC-bearing interval [frac]

A = Gross reservoir area [ac]

B = Initial hydrocarbon formation volume factor [rbbl/stb]

HPT = $h \cdot \phi \cdot (1 - S_{wi})$ = Hydrocarbon pore-thickness [ft]

HPT is calculated mainly based on petrophysical evaluation and it will be underestimated by classic petrophysical evaluation over thin bed laminations intervals.

As can be observed in Figure 1, Gamma Ray log reads high - average 60 GAPI - and resistivity hovers around 2-3 Ohmm. Clean interval is not detected since neutron and density logs don't show cross over. Thin sand laminations interval are colored yellow and thin shale lamination intervals are green. Hydrocarbon pore thickness would be zero by applying normal cutoffs ($GR < 50$ GAPI, $R_t > 3$ Ohmm), which means the interval is

non-reservoir. By testing same interval, only water free hydrocarbon would be produced. The Problem statement for petrophysical evaluation in thin bed laminations can be expressed as: Since thin bed lamination thickness is below conventional log resolution, the true response of pay zone cannot be measured by tools. Hence classical petrophysical workflow underestimates hydrocarbon pore thickness.

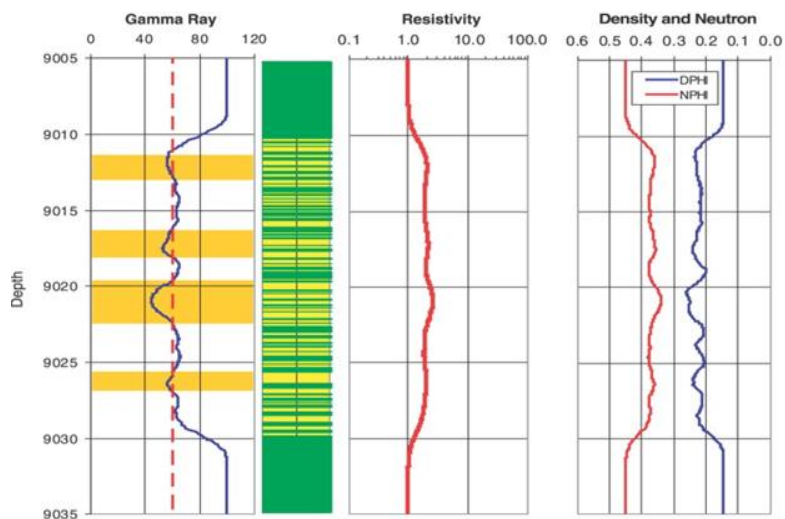


Figure 1. Typical log responses in thin bed interval [10]

Current study aimed to develop a workflow to unlock true potential of low resistivity thin bed lamination intervals, such that evaluated porosity, net to gross and saturation can match true values.

New workflows need to be developed to solve the stated problem. Much research focused on in this domain over decades and various workflows have been proposed and applied. Oil and service companies still develop new workflows in order to assess their thin bed laminated fields accurately. The proposed methods include:

- Volumetric methods as Thomas-Stieber [3], evaluation of induction resistivity log by parallel conductivity model [4,5]
- Laminated Shaly Sand Analysis (LSSA) – a modern tool-based methods by using vertical resistivity [6]
- Nuclear Magnetic Resonance (NMR) based analysis [7]
- Resistivity modeling [8]
- Modern high resolution interpretation workflows as convolution, inversion, deconvolution, forward modeling [9]
- Low resolution workflows as Volumetric Laminated Sandy Shale Analysis (VLSA) [10], Monte Carlo analysis [10]
- Analytic Methods [11]
- Semi analytic [12]
- Numerical simulation methods [13]

Modern evaluation workflows such as convolution, deconvolution, iterative forward modeling, resistivity modeling and inversion made a breakthrough in evaluation of thin shaly sand laminations. [14,15,16] An earth model with some initial properties – e.g., porosity, resistivity – assigned for each thin lamination is convolved by tool response function – convolution filter. The result will be a modeled log. Then modeled log is compared with tool recorded log. Earth model properties should be changed such that the modeled log can be matched by recorded log. A good match confirms true property is assigned in earth model for each thin layer and finally would be used for final petrophysical evaluation. The process is called forward modeling and iterative inversion.

A known deficiency of forward modeling and iterative inversion is non-uniqueness of solutions. It means there can be various earth models by which recorded and modeled logs can be matched. Integrating other disciplines data is necessary to mitigate the mentioned drawback. Earth model lamination thickness and top were just guessed from conventional log data in the previously published researches, which is of high uncertainty since the thickness of thin layers is less than tool resolution. Therefore, lamination picking needs to be confirmed by high resolution data as core photo or image log which never been utilized in previous researches. The mentioned methodology of published researches cannot verify presence of assumed thin layers in earth model and the emphasis was only on obtaining best match of the predicted resistivity log and the recorded resistivity log. Matching the aforementioned logs although is necessary but is not sufficient. There should be ground truth facts and figures to prove the sufficiency of the assumed layering in the applied earth model. In summary there can be a good match of predicted and recorded log but the assumed layering in the earth model is unrealistic.

An important highlight of current research is that in addition to conventional logs, other discipline data as core photo, RCAL and production results were integrated for first time. Hence validity of proposed earth model verified by core photo to ensure avoiding non-uniqueness pitfall. Besides, for the first time, genetic algorithm utilized in order to automate forward modeling and iterative inversion in this research domain and serves as current research novelty.

Genetic Algorithm

Genetic algorithm is a mathematical optimization algorithm inspired by natural evolutionary selection principles. It is widely applied in optimization of different engineering processes and proved to be a successful tool for various engineering areas and oil and gas industry has not been an exception. Some successful applications of genetic algorithm in oil and gas already published [17]. Since this workflow is not available in commercial softwares, a code developed using MATLAB to minimize error function defined as the difference between predicted resistivity log (by forward model) and measured resistivity log which will be discussed in more detail in subsequent sections.

Materials and Methods

Field “A” which is located in Romania is a thin bed sand shale lamination with approximate 5 m gross thickness. It is mainly comprised of sand and shale laminations with limited amount of calcite cement. Permeability is quite high for loose sands and low in shale layers.

Available Data

Fullset log, DST as well as core data are available in Table 1. The interval was logged by 3 porosity logs: Density, Neutron and Sonic logs. Photo electric log is also available. Deep and shallow resistivities were recorded in addition to SP and Gamma Ray log.

Table 1. Available Log and Core Data

Log Data		Core Data	
Log Name	Interval (m)	Core Parameter	Interval (m)
Caliper	10	Porosity	9
SP	10	Permeability	9
Density	10	Grain Density	9
Neutron	10	Oil Saturation	9
Gamma Ray	10	Water Saturation	9
Sonic	10	Description	9
Photo Electric	10	Photo	9
Deep Resistivity	10		
Short Resistivity	10		

Well Log Data

General quality of logs is good since there are no washouts in cored interval Figure 2. Gamma Ray is generally high; it reads minimum 60 GAPI which is not promising to have a prolific clean reservoir. Resistivity curves are overlying which is not indication of permeable interval. Due to having higher resolution, Neutron-Density logs show only a short clean interval (< 0.5 m). Sonic log reads very high (>140 microsec /ft) close to shale. The standard petrophysical evaluation result is plotted in Figure 2. A small oil column (<1m) can be observed. General conclusion is that the reservoir is not prolific up to this point. The well was perforated and produced mainly oil after being tested. Classic petrophysical workflow underestimates oil column. Therefore, we need to update the formation evaluation based on integrating with other data. The first candidate is core data.

Core Data

Core photos confirm presence of sand shale thin lamination, Figure 3. Each column is a 1 m core barrel. Depth increases from left to right which means the left most picture is reservoir top. The first four meters of the core shows oil stain. Oil stain decreases as depth increases. The bottom five meters is almost shale. CCAL data is tabulated in Table 2. There is a large contrast in permeability data which confirms alternation of shale and sand thin laminations. Another important observation is core saturations. Summation of water and oil saturation is not 100%. Error in core saturation is expected when core is not taken under preserved condition. Gas content of oil would vaporize, and oil volume would shrink. Parts of water can also be vaporized into air to reduce original water volume. If water-based mud is used during coring, mud filtrate would replace parts of original oil to decrease oil saturation from original saturation.

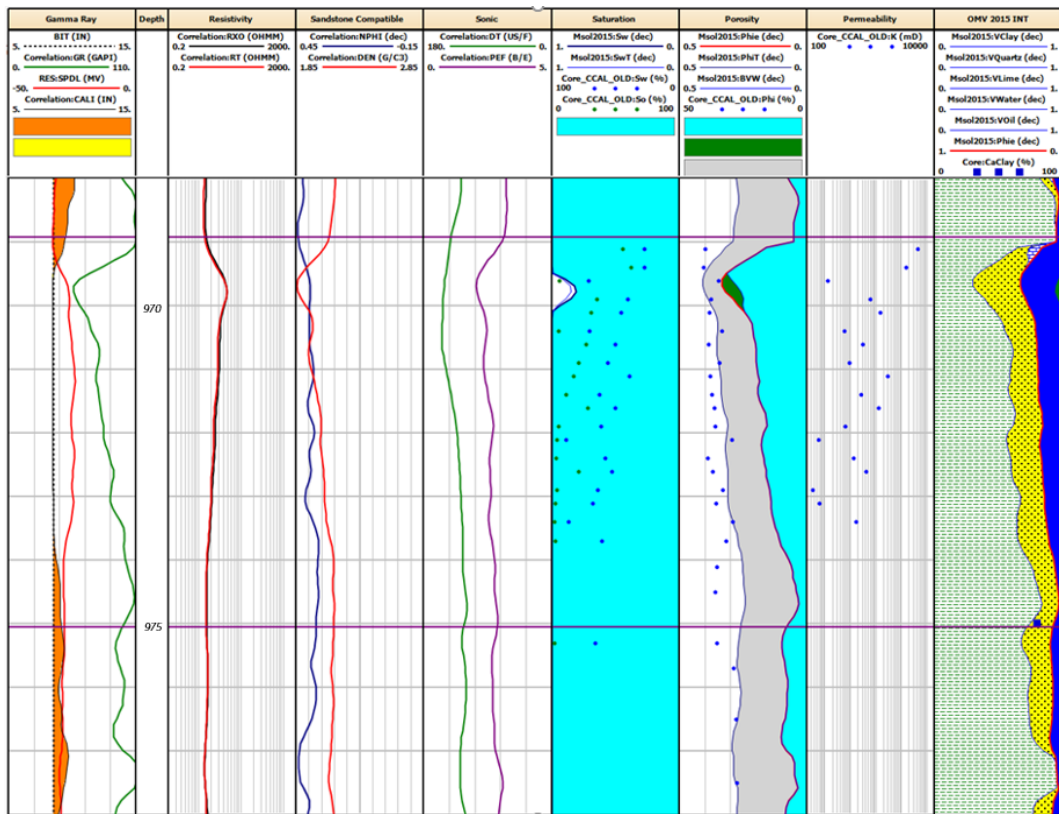


Figure 2. Standard petrophysical evaluation results



Figure 3. Core photo

Table 2. CCAL Data

No.	Phi	GD	K	Sw	So
	%	g/cm ³	mD	%	%
1	39.76	2.66	5401.462	27.55	55.80
2	40.39	2.64	3627.288	27.37	62.10
3	34.74	2.69	213.558	71.37	5.91
4	37.55	2.65	994.480	40.26	35.12
5	38.29	2.66	1399.026	45.91	30.93
6	33.44	2.66	393.297	70.90	5.16
7	38.50	2.66	743.657	50.54	26.61
8	34.40	2.66	470.991	56.30	21.22
9	38.02	2.65	1854.294	39.27	16.79
10	37.19	2.67	711.905	62.43	11.35
11	36.20	2.66	1327.420	50.50	28.32
12	35.92	2.66	405.055	61.74	5.20
13	29.52	2.67	152.461	88.99	4.11
14	38.86	2.68	546.456	57.99	3.44
15	36.98	2.67	857.363	52.99	20.89
16	33.11	2.67	122.533	64.29	3.92
17	35.56	2.67	156.975	68.25	2.72
18	29.15	2.67	588.073	86.92	2.24
19	31.64	2.66	72.460	60.83	2.61
20	35.19	2.68	96.053		
21	36.02	2.68	20.079		
22	35.45	2.65	66.231	65.72	2.00
23	28.66	2.68	11.567		
24	27.76	2.68	2.634		
25	27.31	2.69	1.561		

These are main challenges involved in core saturation measurements. By reviewing core saturations in Table 2, it suggests that the well should mainly produce water, but it produced oil mainly. It can be concluded although core data are highly valuable regarding porosity and permeability, but core saturations can be quite misleading. Hence formation evaluation in thin laminations cannot be done only based on core data.

Earth Model

The main constituents of an earth model are lamination depth, thickness and initial guess for R_t in each thin lamination. Explicit earth model was created based on core photo to define thin lamination thickness Figure 4. Intervals of similar color is considered as a single thin lamination hence have same rock properties.

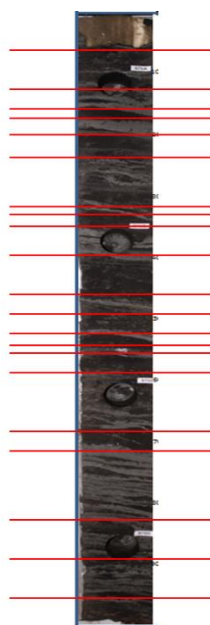


Figure 4. Earth model based on core photo:
defining lamination depth and thickness

In the next step initial R_t in each defined thin lamination would be estimated. Two R_t values will be calculated for each sand laminations since water saturation is not known; Maximum R_t value, based on minimum water saturation (S_w) which is equivalent to irreducible water saturation (S_{wirr}) and a minimum R_t value based on maximum water saturation ($S_w = 100\%$). S_{wirr} can be estimated by rearranging Timur correlation for S_{wirr} .

$$K = a \phi^b / S_{wirr}^c \quad (3)$$

K = Permeability (md)

S_{wirr} = Irreducible Water Saturation (v/v)

ϕ = Porosity (v/v)

$a = 8581$, $b = 4.4$, $c = 2$

Porosity and permeability values were picked from Table 2 and by rearranging Timur formula, S_{wirr} will be estimated. Now this value of S_{wirr} will be inserted in Archie formula to solve it for R_t . Based on this workflow a maximum R_t values were calculated.

If water saturation will be considered 100 %, by solving Archie formula for R_t , a minimum value for R_t will be calculated. The real R_t sand lies within this range so does R_t initial guess. Calculated Maximum R_t and Minimum R_t will be used as check point for the calculated final R_t sand by high resolution formation evaluation method (Forward Modeling and Inversion). The calculation results are tabulated in Table 3. R_t for shale lamination has a limited range of 2–4 Ohmm which can be picked from closest thick shale interval as a valid initial guess which can be updated later during high resolution formation evaluation process. Calculated earth model values for thickness and initial guesses for R_t of each thin lamination which were imported in MATLAB.



Table 3. Calculated Swirr, Maximum Rt and Minimum Rt

No.	Phi v/v	K mD	Swirr v/v	Rt Max Ohmm	Rt Min Ohmm
1	39.76	5401.5	0.17	115.3	3.2
2	40.39	3627.3	0.21	69.9	3.1
3	34.74	213.6	0.62	10.8	4.1
4	37.55	994.5	0.34	30.6	3.5
5	38.29	1399.0	0.3	38	3.4
6	33.44	393.3	0.42	25.4	4.5
7	38.5	743.7	0.42	19.5	3.4
8	34.4	471.0	0.41	25.4	4.2
9	38.02	1854.3	0.26	52.6	3.5
10	37.19	711.9	0.39	23.3	3.6
11	36.2	1327.4	0.27	51.6	3.8
12	35.92	405.1	0.48	16.6	3.9
13	29.52	152.5	0.51	21.9	5.7
14	38.86	546.5	0.5	13.5	3.3
15	36.98	857.4	0.35	29.1	3.7
16	33.11	122.5	0.74	8.4	4.6
17	35.56	157.0	0.76	6.8	4
18	29.15	588.1	0.25	91.5	5.9
19	31.64	72.5	0.87	6.7	5
20	35.19	96.1	0.95	4.5	4
21	36.02	20.1	2.19	0.8	3.9
22	35.45	66.2	1.16	2.9	4
23	28.66	11.6	1.74	2	6.1
24	27.76	2.6	3.4	0.6	6.5
25	27.31	1.6	4.26	0.4	6.7

Tool Response Function

The tool response function for deep resistivity was extracted from previously published works Figure 5 [1]. The curves were digitized and imported in MATLAB. By having earth model and tool response function, forward modeling can be run; earth model should be convolved with tool response function to calculate deep resistivity log value at each depth. By continuing the process for the entire interval, a deep resistivity log would be calculated for the entire interval of interest. The calculated deep resistivity would be overlaid on recorded deep resistivity by tool. If the match is good, it can be concluded the assigned Rt values in earth model are final Rt values. If there is a wide difference between calculated and recorded deep resistivity, the assigned Rt values should be changed to obtain best possible match. This process is called Iterative Inversion. It is not possible to obtain the match by first trials so the process would be repeated many times to obtain the match. This process is time taking so a specific optimization process designed by inclusion of Genetic Algorithm to automate obtaining the final match. This optimization was never applied in previously published researches and is considered to be novelty of this research. All the programming for earth model, convolution, inversion and Genetic Algorithm is done in MATLAB programming software since the codes are not available in commercial Softwares.

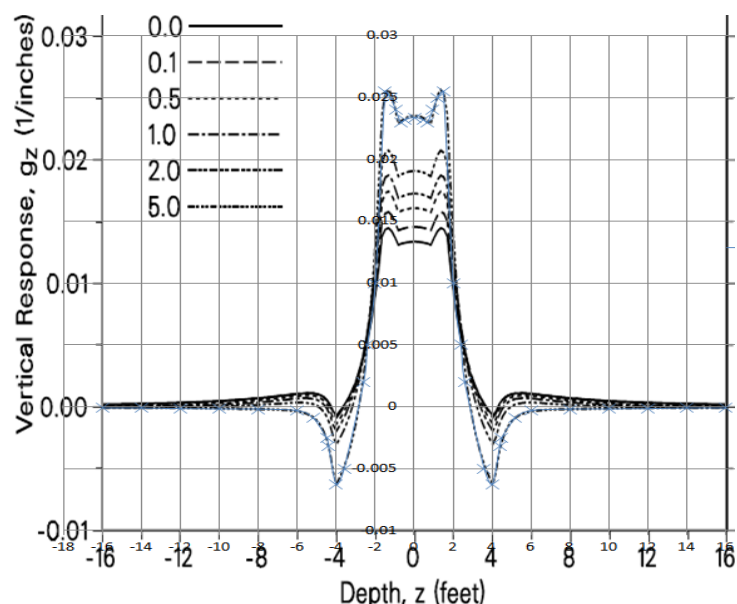


Figure 5. Vertical response function for Deep Resistivity [1]

Results

Well logs were reinterpreted by integrating core data Figure 6. Sand interval and HPT increased considerably. Conventional logs cannot show presence of thin laminations since their thickness is less than log resolution. Topmost 1st meter interval was not perforated, mainly due to the fact that resistivity log readings were low so calculated water saturation was high. It is the limitation of classic Petrophysical workflow.

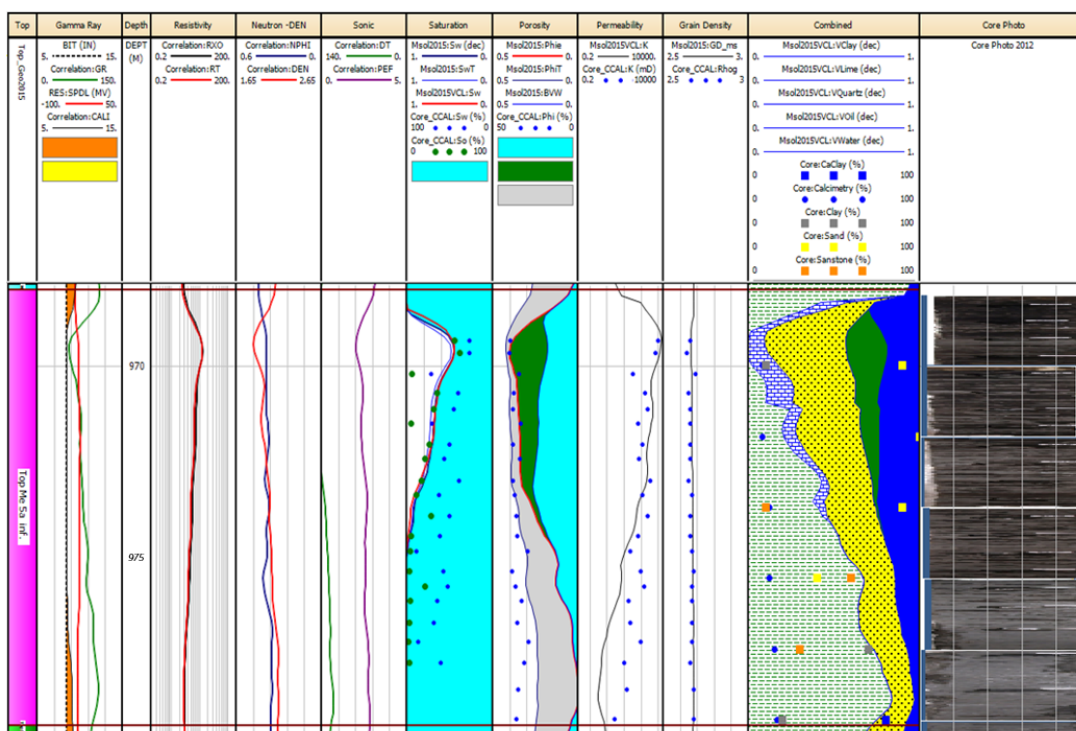


Figure 6. Petrophysical evaluation integrated by core data

In the next step, by the aid of high-resolution evaluation method it will be shown that topmost 1st meter is oil bearing and can get perforated. As mentioned in previous sections, core photo was used for defining shale and sand lamination thicknesses in the earth model. Based on the workflow described in previous sections, initial values for R_t were generated to be incorporated in earth model. All the building blocks are now available to perform forward modeling. Forward model was performed by convolution of earth model and tool response function to generate a calculated (modeled) deep resistivity. In each iteration the difference between calculated log and measured log is considered as an incoherence function. Incoherence function was optimized by the aid of genetic algorithm to produce best possible match between calculated and measured resistivity. The process is illustrated in Figure 7.

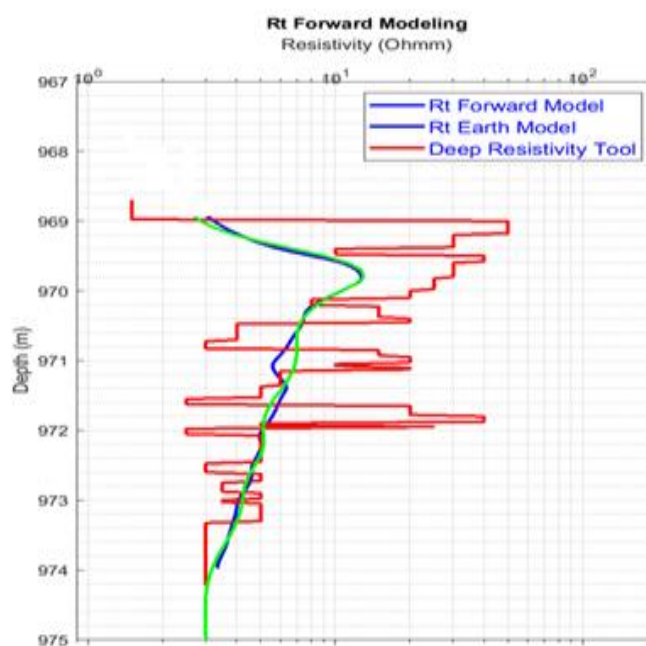


Figure 7. Iterative inversion results

The calculated and predicted resistivity match was improved step by step till the error was less than a predefined criterion and then iteration process stopped. Based on the results, it is observed that topmost 1st meter is also reservoir and can be perforated as is confirmed by the Figure 7; the calculated Earth Model R_t – red curve – will be the resistivity log which would be used for true S_w calculation. The range of calculated R_t in sand thin lamination is higher than the measured resistivity so it guaranties to interpret high oil saturation up to topmost part of reservoir – at 696 m; therefore, hydrocarbon column was added up to 30%. Besides the calculated R_t reads low in bottom parts of interval even in sand zones, so it is expected to have higher water saturation in lower parts of interval. The well test result confirmed 70% oil and 30% water production.

Earth models were developed based on trial and error using conventional logs, in previously published researches and hence were not verified by high resolution data. In other words, thickness, top and base of thin laminations were guessed which imposed a great uncertainty. But in current study the validity of proposed earth model verified by high resolution data – core photo. Proposed workflow is an improvement to Schlumberger SHARP Processing.

In the absence of core photo, image logs are equally applicable to define thin lamination thickness, top and base. The only difference is that maximum and minimum R_t cannot be calculated for initial guess for R_t . The process of making a valid initial guess for R_t sand, enhances convergence rate to true sand lamination resistivity but the rest of workflow is applicable for image log case as well; the process may not be as fast as when initial guess for R_t sand is not available.

CONCLUSION

Forward modeling and inversion were successfully applied in evaluation of low resistivity low contrast (LRLC) thin shale sand lamination and hence enhanced hydrocarbon column. The topmost interval was considered to be non-reservoir based on classic petrophysical workflow, so was not perforated. Based on the results of the current study, top interval is also hydrocarbon bearing and recommended to get perforated.

It was concluded that classic Petrophysics underestimates true hydrocarbon pore thickness in thin shale sand lamination since layer thickness is less than log resolution, therefore rock properties of several successive thin sand shale lamination are averaged and stacked at each depth and is not representative for each thin laminae rock property.

Matching calculated (modeled) and measured deep resistivity match, although is necessary but is not sufficient; the results should get validated by other data sources as core, advanced logs, production test results, etc. Creating an accurate earth model needs high resolution data as core photo or image log. These are the drawbacks in previously published work in this domain.

A very important power point of this research is integration of fullset logs, RCAL, core photo and production test results which have not been reported in any of previous published papers. Therefore, validity of earth model is confirmed by core photo to avoid non- uniqueness of solutions.

A new algorithm was developed for automating optimization of forward modeling and inversion by using genetic algorithm which is the novelty of this research. The proposed algorithm performance was validated by other data integration. Proposed workflow is an improvement of Schlumberger SHARP Processing.

A computer code developed in this research to perform the mentioned workflow since aforementioned capabilities is not available in commercial softwares. The proposed method is practically applicable to thin bed laminations of several inches and thicker. For very thin laminations as turbidites, other methods as Thomas Stieber and statistical methods as VLSA and Monte Carlo are recommended.

Table 4 summarizes workflows of formation evaluation in shaly sand lamination based on different available data sets.

Table 4. Workflow of petrophysical evaluation in shale sand lamination

Input Data	Method	Earth Model	Initial sub layer Resistivity	Processing	Interpretation
1. Core: Photo and CCAL 2. Deep resistivity logs 3. Tool Response Function	Forward Modeling / Inversion	Define Earth Model thickness and sub layer depths based on core photo	Calculate primary guess for resistivity based on combined Timur and Archie models	Run forward model and iterative inversion to calculate true sand resistivity	Define reservoir NTG based on core photo, calculate Sw based on true sand resistivity obtained from inversion
1. Image Log or Core Photo 2. Deep resistivity logs 3. Tool Response Function	Forward Modeling / Inversion	Define Earth Model thickness and sub layer depths based on Image log / Core photo	Assign primary resistivity guess to be in range for shale (2-4 Ohmm) and sand (> 4 Ohmm)	Run forward model and iterative inversion to calculate true sand resistivity	Define reservoir NTG based on image log, calculate Sw based on true sand resistivity obtained from inversion
1. Conventional Logs 2. Tool Response Function	Forward Modeling / Inversion	Define Earth Model thickness and sub layer depths based on Neutron Density and short resistivity fluctuation	Assign primary resistivity guess to be in range for shale (2-4 Ohmm) and sand (> 4 Ohmm)	Run forward model and iterative inversion to calculate true sand resistivity	Define reservoir NTG based on true sand resistivity, calculate Sw based on true sand resistivity obtained from inversion
1. Conventional Logs 2. Vertical Resistivity	LSSA			Solve Vertical and horizontal permeability simultaneously to obtain true sand resistivity	Calculate saturation based on obtained true sand resistivity
Conventional Logs	Thomas-Stieber Analysis			Calculate laminated clay Volume (V _{lam}) and dispersed clay volume (V _{dis})	Calculate Sw from Poupon saturation model by V _{lam} , V _{dis} and deep resistivity
1. Conventional Logs 2. Core or Image Log 3. Detailed Resistivity Tool Design		Define Earth Model thickness and sub layer depths, based on Core Photo or Image log	R _t max and R _t min based on core / Initial guess which is in range for Image log case	Solve Maxwell Electromagnetic law over 3D grid to obtain each grid conductivity	Calculate saturation based on obtained grid conductivity

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